

Observations of Very Metal-Poor Stars in the Galaxy

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Abstract.

I report on recent results from observations of stars with metallicities $[\text{Fe}/\text{H}] \leq -2.0$. These include a substantial new sample of objects with high-resolution observations obtained as part of a follow-up of the HK Survey, The Hamburg/ESO Survey, and the ongoing survey SEGUE: Sloan Extension for Galactic Understanding and Exploration. Perspectives on the next directions are also provided.

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THE IMPORTANCE OF VERY METAL-POOR STARS

It is widely recognized that stars with metallicities less than 1% of the solar value ($[\text{Fe}/\text{H}] < -2.0$; the Very Metal-Poor (VMP) stars in the nomenclature of Beers & Christlieb [1] provide invaluable information on the origin of the elements in the Universe, and on the nature of the neutron-capture processes that were the dominant source of the elements beyond the iron peak. Perhaps less appreciated is the fact that these same stars place strong constraints on the formation and evolution of individual galaxies, and thereby provide a direct connection with cosmological studies. Within the Milky Way, the shape of the low-metallicity tail of the Metallicity Distribution Function (MDF) is beginning to reveal the characteristic abundances of elements associated with the major epochs of star formation in the early Galaxy. Changes in the MDF as a function of distance are revealing the assembly history of the Galaxy (see, e.g., the article by Carollo & Beers in this volume). The frequency of various abundance signatures, e.g., the $[\text{C}/\text{Fe}]$ and $[\alpha\text{-element}/\text{Fe}]$ ratios, are being used to investigate the dominant production sites, and the Initial Mass Function (IMF) of the stellar populations in the proto-Galactic fragments that theory suggests were involved in galaxy assembly. In this short review, I summarize a few of the recent observational results, and indicate the directions which the field will be going in the next few years.

PAST AND ONGOING SURVEYS

Past searches for VMP stars include those based on the selection of high proper-motion stars in the local volume [e.g., 2, 3], and in particular, stars identified from non-kinematically biased *in-situ* objective-prism surveys, such as the HK survey of Beers

and colleagues [4, 5], and the more recent Hamburg/ESO Survey (HES) of Christlieb and collaborators [6]. These two surveys form the basis for the majority of the high-resolution spectroscopic studies that have been carried out over the past decade, such as the First Stars program of Cayrel et al. [7], the HERES project of Barklem et al. [8], and the 0Z Project of Cohen et al. [9].

Although work continues on the medium-resolution follow-up of HK and HES candidate VMP stars, to date the efforts have yielded roughly 2500 firm identifications. However, it should be emphasized that as these stars are selected in the volume surrounding the Sun, and explore no more than 10 kpc (in the case of the HK survey) to 15 kpc (in the case of the HES) away, these samples are dominated by the now-recognized inner-halo population of the Galaxy [10]. The outer-halo population, which Carollo et al. suggest is comprised of a MDF with peak metallicity a factor of three times lower ($[\text{Fe}/\text{H}] = -2.2$) than that associated with the inner halo ($[\text{Fe}/\text{H}] = -1.6$), dominates outside of 15-20 kpc from the Galactic center. This may well account for the difficulty in the identification of significant numbers of stars at the lowest metallicities, the Ultra Metal-Poor (UMP) and Hyper Metal-Poor (HMP) stars, with $[\text{Fe}/\text{H}] < -4.0$ and $[\text{Fe}/\text{H}] < -5.0$, respectively. If progress is to be made in finding large numbers of such stars, different tactics must be explored.

Fortunately, this process has already begun. Already, the largest numbers of VMP stars revealed to date has emerged from medium-resolution spectroscopic spectra taken during the course of the SDSS (primarily calibration stars) and SEGUE. SEGUE is a survey directed at studies of Galactic structure, but it includes a number of target categories (such as F turnoff stars, K giants, and a low-metallicity category extending across all spectral types) that is successful in the identification of large numbers of VMP stars. Even though SEGUE is not yet complete, the total list of VMP stars already exceeds 10,000 stars, quadruple the number from the HK/HES efforts combined. Of greatest importance, SDSS/SEGUE can explore to much larger distances, beyond the 10-15 kpc region where the inner-halo population dominates. Furthermore, the availability of reasonably accurate proper motions for the subset of nearby stars (out of 4-5 kpc from the Sun) makes it feasible to identify candidate VMP, EMP, UMP, and HMP stars based on the characteristic retrograde signature of the outer-halo population. This mode of selection has not been implemented in SEGUE, but it is one of the target categories that will be explored in the SEGUE-2 project, which will be executed from July 2008 to July 2009 as part of the proposed next extension of the Sloan Survey, known as SDSS-III (see <http://www.sdss3.org/outermilkyway.php>). We are hopeful that this dedicated effort will finally be able to break through the UMP/HMP barrier.

Space precludes a comprehensive discussion of even the most recent results coming from high-resolution spectroscopic studies of VMP stars, so below I simply summarize a few of the results of greatest relevance to this conference. Other examples can be gleaned from the online version of my talk.

RECENT RESULTS

Carbon-Enhanced Metal-Poor (CEMP) stars

The CEMP stars (and their sub-categories) are defined by Beers & Christlieb [1] based on the criteria listed in Table 1. Their clear significance to understanding the chemical evolution of the Galaxy results from the apparently large fraction of such stars that are found among the VMP stars (which varies between 10% and 20%, according to investigations carried out to date). At the lowest iron abundances, CEMP stars represent 40% of stars with $[\text{Fe}/\text{H}] < -3.5$ [1], and 100% (3 of 3) of stars known with $[\text{Fe}/\text{H}] < -4.0$ [11, 12, 13]. A number of articles in this volume discuss attempts to understand the origin of the UMP and HMP CEMP stars.

TABLE 1. Definition of sub-classes of metal-poor stars (based on Beers & Christlieb [1])

Carbon-enhanced metal-poor stars	
CEMP	$[\text{C}/\text{Fe}] > +1.0$
CEMP-r	$[\text{C}/\text{Fe}] > +1.0$ and $[\text{Eu}/\text{Fe}] > +1.0$
CEMP-s	$[\text{C}/\text{Fe}] > +1.0$, $[\text{Ba}/\text{Fe}] > +1.0$, and $[\text{Ba}/\text{Eu}] > +0.5$
CEMP-r/s	$[\text{C}/\text{Fe}] > +1.0$ and $0.0 < [\text{Ba}/\text{Eu}] < +0.5$
CEMP-no	$[\text{C}/\text{Fe}] > +1.0$ and $[\text{Ba}/\text{Fe}] < 0$
Neutron-capture-rich stars	
r-I	$+0.5 \leq [\text{Eu}/\text{Fe}] \leq +1.0$ and $[\text{Ba}/\text{Eu}] < 0$
r-II	$[\text{Eu}/\text{Fe}] > +1.0$ and $[\text{Ba}/\text{Eu}] < 0$
s	$[\text{Ba}/\text{Fe}] > +1.0$ and $[\text{Ba}/\text{Eu}] > +0.5$
r/s	$0.0 < [\text{Ba}/\text{Eu}] < +0.5$

Aoki et al. [14] reports new observations (obtained with the Subaru telescope) and summarizes results from the high-resolution studies of CEMP stars reported in the literature. Among the most intriguing results from this study concerns the apparent difference in the MDFs (see Figure 1) between the CEMP-s (those exhibiting abundance signatures characteristic of the s-process, and which likely originated from mass-transfer events from a now-deceased intermediate mass AGB companion) stars, and the CEMP-no (those exhibiting no neutron-capture elements, and whose origin remains the subject of current discussion) stars.

Aoki et al. [15] presents additional Subaru results for a small sample (seven) of CEMP stars selected from SDSS/SEGUE to be located at the main-sequence halo turnoff. These stars are important because they lie in the region of the H-R diagram where there is no possibility of extensive mixing of their outer atmospheres having taken place (at least via usual mechanisms); they thus represent an essentially pure signature of the elemental abundance patterns produced by their progenitors. It is of interest that the majority of the CEMP stars in this study exhibit kinematics that may associate them with the outer-halo population reported by Carollo et al. [10].

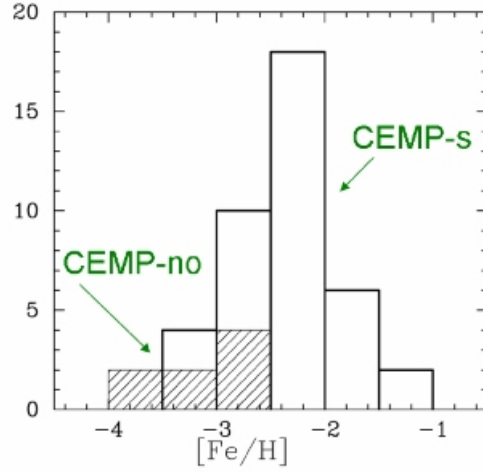


FIGURE 1. Distribution of $[C/Fe]$ for CEMP stars discussed by Aoki et al. [14]. Note the predominance of the CEMP-no stars (cross-hatched bars) at the lowest $[Fe/H]$.

Another recent study has measure the abundance of flourine (F) in a CEMP-s star [16, see Figure 2], using the Phoenix near-IR high-resolution spectrograph on the Gemini-S telescope. This observation represents the first such detection in a CEMP star (and revealed this star to have an over-abundance $[F/Fe] = +2.9$, nearly 1000 times that of the solar ratio). This element provides a sensitive probe of the operation of the s-process in AGB stars [e.g., 17], and may provide information on the IMF from which the AGB progenitor was drawn [18]. Additional high-resolution spectroscopy of CEMP stars for the study of this element are clearly required.

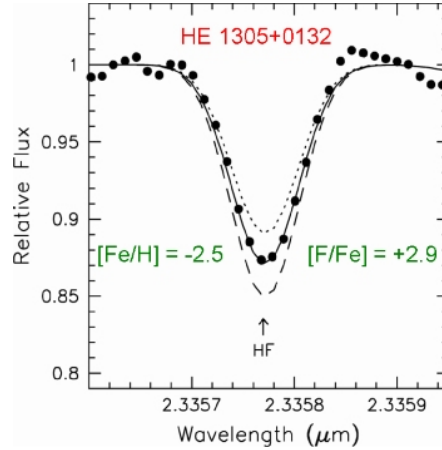


FIGURE 2. The detection of F in a VMP CEMP star by Schuler et al. [16]; the HF molecular feature is very prominent.

Among the recent theoretical studies of the significance of the CEMP stars, I draw attention to the work of Tumlinson [19], which has argued that the critical mass of early star formation in the Universe was shifted to favor the formation of intermediate-mass stars (essentially due to the “floor” set by the cosmic microwave background temperature

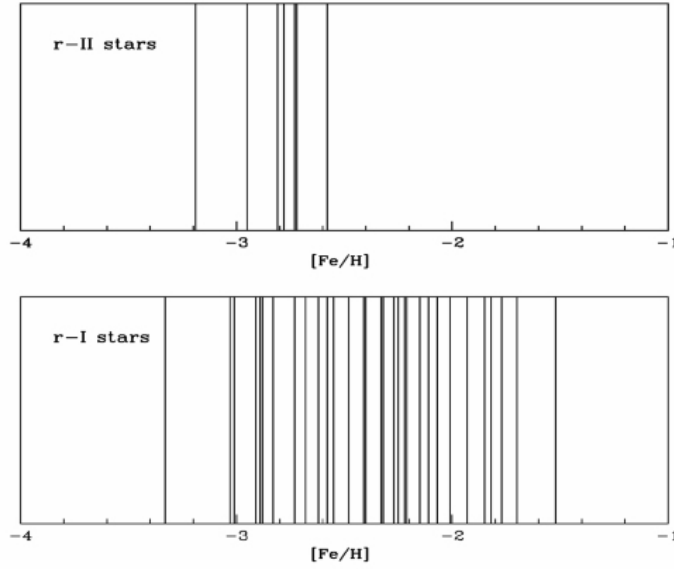


FIGURE 3. Distribution of $[\text{Fe}/\text{H}]$ for r-process-enhanced stars identified by Barklem et al. [8]. Note the obvious contrast between the behavior of the r-II stars with that of the r-I stars.

at the time) that are copious carbon producers. Others [e.g., 20, 21] have argued that significant carbon (and nitrogen) may be produced from the winds of massive Mega Metal-Poor (MMP; $[\text{Fe}/\text{H}] < -6$), rapidly rotating stars that might have formed at the very earliest epochs of the Universe. Such stars would not be expected to produce s-process elements, but their association with the origin of the CEMP-no stars has yet to be established.

Highly r-process-enhanced stars

One of the goals of the HERES survey of Barklem et al. [8] was to dramatically increase the numbers of VMP stars with enhanced r-process elements. This goal was met; eight new examples of the phenomenon were identified, and a critical difference was noted between the MDF of the so-called r-II stars (those with $[\text{Eu}/\text{Fe}] > +1.0$, and low Ba, according to Table 1), and the moderately r-process-enhanced stars ($+0.5 \leq [\text{Eu}/\text{Fe}] < +1.0$). As is clear from Figure 3, while the r-I stars exhibit an MDF that covers a wide range, the MDF of the r-II stars is restricted to roughly $-3.2 < [\text{Fe}/\text{H}] < -2.6$.

An additional handful of r-II stars have since been identified by other studies, including at least one with detected uranium ([22]; HE 1523-0901, with $[\text{Fe}/\text{H}] = -2.95$); others are still unpublished. It is presumably no coincidence that *all* of the newly discovered r-II stars fall in the same low metallicity interval as those from the Barklem et al. study. One possible explanation is that the main astrophysical r-process arises from stars of a relatively small mass range (many have suggested $10\text{-}15 M_{\odot}$), which may have been the dominant contributor of heavy elements at the time when the Galaxy

reached a mean metallicity around $[\text{Fe}/\text{H}] \sim -3.0$. Other alternatives surely exist.

Observations of light n-capture elements

Although the stars with large enhancements of n-capture elements are of great interest, it is equally important to consider the abundances of n-capture elements for the great majority of metal-poor stars with “normal” levels, as these help constrain the question of the universality of the r-process, and address whether multiple r-process sites must be considered. Recently, Francois et al. [23] reported abundance determinations for some 16 n-capture elements for a sample of 32 VMP and EMP stars observed during the course of the Cayrel et al. First Stars program. These data greatly enlarge the numbers of stars with $[\text{Fe}/\text{H}] < -2.8$ with such measurements available. The star-to-star scatter among these elements reaches a peak at around $[\text{Fe}/\text{H}] = -3.0$, but below this metallicity, too few stars exist with measurements to be certain of the behavior.

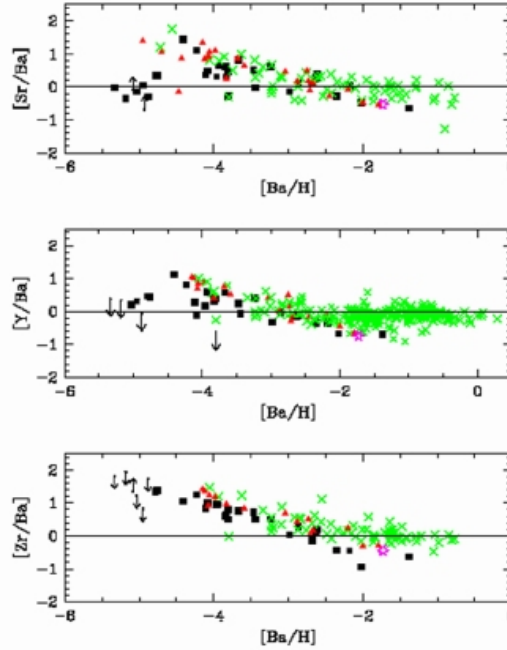


FIGURE 4. Reported abundances for Sr, Y, and Zr, relative to Ba, as a function of $[\text{Ba}/\text{H}]$, from Francois et al. [23]. The new data are shown as the black squares (or upper limits). Other data are from the literature.

By adopting the element Ba as a reference element, Francois et al. demonstrate the existence of strong anti-correlations of the lighter n-capture ratios $[\text{Sr}/\text{Ba}]$, $[\text{Y}/\text{Ba}]$, and $[\text{Zr}/\text{Ba}]$ with the $[\text{Ba}/\text{H}]$ abundance from $[\text{Ba}/\text{H}] \sim -1.5$ down to $[\text{Ba}/\text{H}] \sim -4.5$ (Figure 4). It remains unclear if this behavior changes below $[\text{Ba}/\text{H}] = -4.5$, as only upper limits on the lighter element ratios are available for the majority of stars in this region; the few measurements that *do* exist suggest a possible reversal of the trends observed above this limit. In any case, the results confirm that there must exist a second n-capture process to account for the synthesis of the first r-process peak elements, variously referred to

in the literature as the “weak” r-process [24] or the Light Element Production Process [LEPP 25]. Subtraction of the predicted contributions to these elements by the main r-process suggests that this mechanism is responsible for the production of 90-95% of the observed amount of Sr, Y, and Zr in stars with $[\text{Ba}/\text{H}] > -4.5$. See Montes et al. [26] for additional discussion of the LEPP.

NEW AND ANTICIPATED HIGH-RESOLUTION SPECTROSCOPIC STUDIES

There exist a number of large high-resolution spectroscopic surveys that are just now getting underway, which should greatly enlarge the numbers of VMP stars with available elemental abundance information. The Chemical Abundances of Halo Stars (CASH) survey is making use of the Hobby-Eberly Telescope to obtain moderately high-resolution ($R = 15,000$) spectroscopy for up to 1000 VMP stars identified during the course of the HK-I, HK-II, and HES efforts, with a large number of additional stars from SDSS/SEGUE. Aoki et al. have recently been awarded a Key Project status on the Subaru Telescope, with the aim of obtaining $R = 50,000$ spectroscopic observations for up to 200 VMP stars, the majority of which will be drawn from SDSS/SEGUE targets. Both of these surveys have as one of their primary aims to test for the existence (or not) of chemical signatures that might be associated with the inner/outer halo dichotomy reported by Carollo et al. [10].

In the near future, the proposed SDSS-III project will undertake a massive survey of some 100,000 red giants with resolving power $R = 20,000$, concentrating on the H-band region in the near-IR. This survey, known as APOGEE (APO Galactic Evolution Experiment; see <http://www.sdss3.org/innermilkyway.php>) is expected to take place between 2011 and 2014, and will target objects in the Galactic bulge, bar, disk, and halo components. It is expected that on the order of 15 individual elements will be obtained per star.

Of course, we all look forward to the possible execution of the WFMOS (Wide Field Multi-Object Spectrograph) survey of on the order of one million stars at resolving power $R = 50,000$. Currently, this Gemini instrument is expected to be mounted on the prime focus of the Subaru telescope, in order to take advantage of its wide field of view. The hope, and expectation, is that this survey will finally reveal the elemental abundances of stars that probe the entire history of chemical evolution throughout the Galaxy.

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